Proceedings of the Geologists' Association 124 (2013) 883–892

Contents lists available at SciVerse ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

Review paper

Late Silurian–Middle Devonian long-term shoreline shifts on the northern Gondwanan margin: eustatic versus tectonic controls

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ARTICLE INFO

Article history:
Received 23 October 2012
Received in revised form 15 December 2012
Accepted 20 December 2012
Available online 24 January 2013

Keywords:
Transgression
Regression
Eustasy
Dynamic topography
Gondwana
Middle Paleozoic

ABSTRACT

Long-term shoreline shifts reflect eustatic changes, tectonic activity, and sediment supply. Available lithostratigraphical data from northern Africa, Arabia, and the Tethys Hymalaya, coupled with facies interpretations, permit us to trace late Silurian–Middle Devonian long-term shoreline shifts across the northern Gondwanan margin and to compare them with constraints on global sea-level changes. Our analysis establishes a regression–transgression cycle. Its coincident global sea-level changes reveal the dominance of the eustatic control. A transgression–regression cycle observed in Arabia is best explained by regional subsidence. Our study highlights the importance of constraining the role of regional tectonics when interpreting shoreline shifts.

Contents

1. Introduction

Global sea level has experienced multi-order fluctuations during geologic history, which may have either common or different causes; moreover, the regional imprints of these fluctuations may differ geographically because they can be complicated by spatial variations in vertical tectonic motions and sediment supply (Vail et al., 1977; Hallam, 1984, 2001; Haq et al., 1987; Haq and Al-Qahtani, 2005; Miller et al., 2005; Catuneanu, 2006; Cogné et al., 2006; Nerem et al., 2006; Cazenave et al., 2008; Cogné and Humler, 2008; Haq and Schutter, 2008; Müller et al., 2008; Conrad and Husson, 2009; Kirschner et al., 2010; Lovell, 2010; Miall, 2010; Catuneanu et al., 2011; Kemp et al., 2011; Ruban, 2011a; Jones et al., 2012; Meyssignac and Cazenave, 2012; Ostanciaux et al., 2012; Ruban et al., 2012; Spasojevic and

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0016-7878/$ – see front matter
http://dx.doi.org/10.1016/j.pgeola.2012.12.004

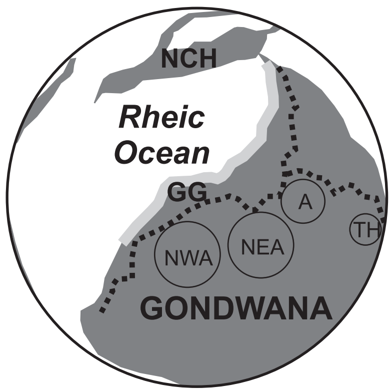

Fig. 1. Plate tectonic setting of the Northern Gondwanan margin near the Silurian-Devonian transition and the approximate position (circles) of the studied regions (the base map is strongly simplified from von Raumer and Stampfli, 2008). Major land masses and oceans are shown by dark grey and white, respectively. Light grey line indicates obduction along the Rheic Ocean, and dashed black line traces the future margins of the Paleo-Tethys Ocean. Abbreviations: A, Arabia; GG, Greater Galatian Superterrane; NCH, North China with accreted Hunia; NEA, northeastern Africa; NWA, northwestern Africa; TH, Tethys Himalaya.

Gurnis, 2012). For instance, it is assumed that shoreline shifts, i.e., transgressions (landward shifts) and regressions (seaward shifts) (sensu Catuneanu, 2006) are linked primarily to eustatic rises and falls, but regional tectonic activity affects their amplitudes and may even reverse these trajectories (e.g., Ruban, 2007a, 2011a; Moucha et al., 2008; Ruban et al., 2012). This is why establishing regional shoreline shifts of different orders and deciphering their eustatic and tectonic controls are always challenging tasks.

The Paleozoic northern Gondwanan margin (Fig. 1), which included the northern parts of Africa, all of Arabia, and numerous adjacent terranes (Metcalfe, 1999, 2011; Cocks and Torsvik, 2002; Stampfli and Borel, 2002; Scotese, 2004; Torsvik and Cocks, 2004, 2011; Ruban et al., 2007a; von Raumer and Stampfli, 2008; Greff-Lefftz and Besse, 2012; Nance et al., 2012; Wilhem et al., 2012), is a promising location for studies of shoreline shifts. On the one hand, this was a rather 'stable' cratonic domain (e.g., Stampfli and Borel, 2002; Guiraud et al., 2005). On the other hand, it did not escape significant tectonic influences (e.g., Guiraud et al., 2005; von Raumer and Stampfli, 2008). Moreover, a series of works synthesizing Paleozoic lithostratigraphy of the major parts of this margin were published during the past decade (Sharland et al., 2001; Guiraud et al., 2005; Raju, 2007; Simmons et al., 2007), which permits judgements of transgressions and regressions.

Our present analysis differs from earlier studies (Ruban, 2007b, 2011a,b) because it focuses only on long-term shoreline shifts, i.e., recognizable at a scale of epochs and periods (to be of the same frequency as the long-term global sea-level changes depicted by Haq and Schutter (2008)), which occurred on the northern Gondwanan margin during the late Silurian–Middle Devonian. This geologic time interval has been chosen for two reasons. Firstly, it corresponds to a complete long-term eustatic cycle (Fig. 2) with global sea-level fall in the late Silurian, a peak lowstand in the Early Devonian, and global sea-level rise in the Middle Devonian (Haq and Schutter, 2008). Secondly, this interval was characterized by the persistence of obduction along the northern Gondwanan margin before the opening of the Paleo-Tethys Ocean in the Middle-Late Devonian (von Raumer and Stampfli, 2008). Two main objectives of this study are to envisage the long-term shoreline shifts in the studied domain and to evaluate the relative importance of eustasy and regional tectonics as their possible controls.

2. Geodynamic setting

Gondwana was a single supercontinent in the mid-Paleozoic, and its northern margin included both cratonic domains and peripheral terranes (Cocks and Torsvik, 2002; Stampfli and Borel, 2002; Torsvik and Cocks, 2004, 2011; Scotese, 2004; von Raumer and Stampfli, 2008; Greff-Lefftz and Besse, 2012). The cratonic domains constitute present-day northwestern and northeastern Africa and Arabia, whereas the fate of the peripheral terranes is determined more ambiguously. Stampfli and Borel (2002)

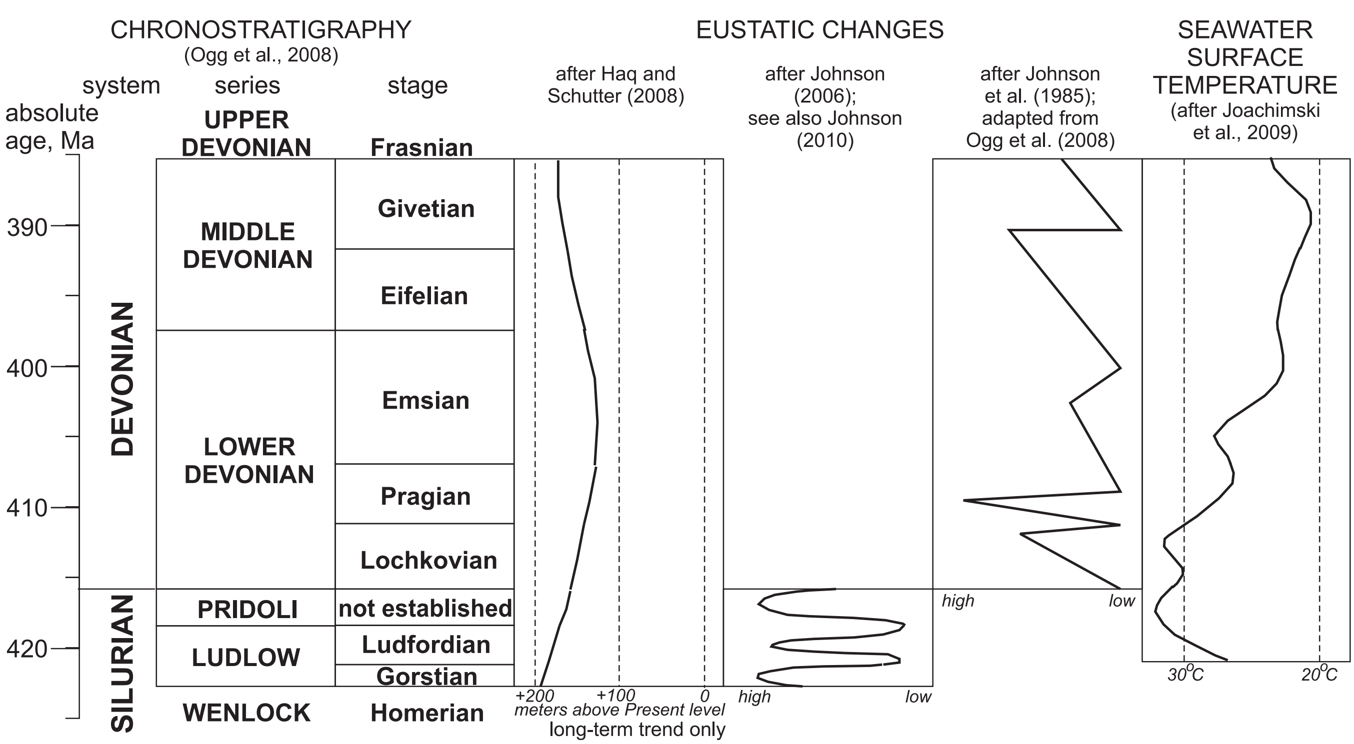

Fig. 2. Chronostratigraphy, eustatic changes, and seawater surface temperature of the studied geologic time interval. See Ref. Joachimski et al. (2009).

suggested a separation of the long chain of tectonic blocks, i.e., the so-called Hun Superterrane, off Gondwana with the subsequent opening of the Paleo-Tethys Ocean and the closure of the Rheic Ocean in the Silurian. More or less comparable views were expressed by Cocks and Torsvik (2002), Scotese (2004), Torsvik and Cocks (2004, 2011), Ruban et al. (2007a), and Metcalfe (2011). Later, von Raumer and Stampfli (2008) revised their model strongly and suggested that the separation of the superterrane (now called the Greater Galatian Superterrane) occurred only in the Middle-Late Devonian; this was preceded by the collision of an island arc with the peripheral terranes, which resulted in obduction (Fig. 1). This updated understanding of the mid-Paleozoic geodynamics of the northern Gondwanan margin is followed in this paper. Most recently, Nance et al. (2012) suggested that the Rheic Ocean started closing since the beginning of the Devonian and also noted that the geodynamics of the peripheral terrane ribbon is questionable and requires further investigation.

The present study focuses on such major cratonic domains as northwestern Africa, northeastern Africa, and Arabia, and also involves data from the terrane of the Tethys (=Tethyan) Himalaya (Fig. 1). Consideration of these regions permits us to trace late Silurian–Middle Devonian shoreline shifts across almost the entire northern Gondwana margin. The noted cratonic domains formed a consolidated continental mass, which, however, experienced a series of relatively short-term tectonic deformations (like those across the Silurian-Devonian transition) and permanent vertical motions (Sharland et al., 2001; Guiraud et al., 2005; Ruban et al., 2007a). The latter created a puzzle of subsided and uplifted areas on the northern Gondwanan margin. As for the Tethys Himalaya, this is a large terrane, which separated off Gondwana only in the late Paleozoic to become one of the Cimmerian terranes that moved northwards together with the closure of the Paleo-Tethys Ocean and the opening of the Neo-Tethys Ocean (Torsvik et al., 2009; Ran et al., 2012; Sciunnach and Garzanti, 2012). Despite debates on its tectonic consolidation with the cratonic domain of India (Cocks and Torsvik, 2002; Torsvik and Cocks, 2004; Torsvik et al., 2009; Ran et al., 2012), which are difficult to resolve because of voluminous consumption of the terrane's crust due to the Eurasia-India collision (Ran et al., 2012), the lithostratigraphical data from the Tethys Himalaya (Raju, 2007) provide valuable evidence of Paleozoic shoreline shifts in the Indian (sensu lato) sector of the Gondwanan margin: such data from continental India itself are scarce (cf. Ruban, 2011a).

3. Materials and methods

The present study is based on the already-compiled lithostratigraphical data coupled with facies interpretations from four regions of the northern Gondwanan margin. For northwestern and northeastern Africa, the synthesis by Guiraud et al. (2005) is used. In that work, the position of the shoreline for three major time slices, namely the Silurian, the Early Devonian, and the Middle-Late Devonian, is also depicted on paleomaps. For Arabia, we refer to the synthesis by Sharland et al. (2001). Data from there, including the absolute ages of sequence boundaries and maximum flooding surfaces, are considered according to the later interpretations attempted by Simmons et al. (2007). Finally, the synthesis by Raju (2007) provides the essential lithostratigraphical and facies data for the Tethys Himalaya. The resolution of the litho- and chronostratigraphical frameworks employed in the above-mentioned sources is high (in the case of Arabia) to moderate (in the cases of northern Africa and the Tethys Himalaya), and it is overall sufficient to establish long-term shoreline shifts. This study employs chronostratigraphy recommended by the International Commission on Stratigraphy (Ogg et al., 2008; see also on-line: www.stratigraphy.org) (Fig. 2). Some other relevant recent viewpoints (e.g., by Menning et al., 2006; Cocks et al., 2010) are also considered. It should be noted that there is an alternative proposal for the absolute ages of the Devonian stage boundaries (Kaufmann, 2006). All formal units are capitalized (e.g., Early Devonian), whereas those that are informal are not (e.g., late Silurian).

Methodologically, this study is based on three general principles. Firstly, transgressions and regressions can be registered only by the lateral displacement of facies through geologic time, and not by changes in the water depth (although these two patterns are interconnected sometimes) (Ruban, 2007a). Secondly, it is assumed that changes in global sea level (=eustatic changes) drive shoreline shifts directly (see also Ruban, 2011a; Ruban et al., 2012). Thirdly, an absence of coincidence between the regional shoreline shift and the global eustatic change indicates the influence of either regional tectonic activity or "abnormal" sediment supply (Ruban, 2011a). The authors also share the view that there are neither absolutely stable regions (even if these are old cratonic domains) nor strictly passive margins (cf. Lithgow-Bertelloni and Gurnis, 1997; Lithgow-Bertelloni and Silver, 1998; Stoker and Shannon, 2005; Heine et al., 2008; Moucha et al., 2008; Müller et al., 2008; Conrad and Husson, 2009; DiCaprio et al., 2009; Lovell, 2010; Japsen et al., 2012; Ruban et al., 2012; Shephard et al., 2012). Moreover, we cannot exclude the possibility that eustatic reconstructions, such as the one attempted by Haq and Schutter (2008), incorporate some effects of regional tectonic activity because they are based essentially on regional data.

The first step in our analysis is establishing long-term shoreline shifts in each of the particular major domains of our study region. This permits us to envisage common patterns and to judge the homogeneity or heterogeneity of shoreline shifts along the northern Gondwanan margin. Stratigraphic distribution of hiatuses, continental versus marine facies architecture, and interpreted positions of the shorelines, sequence boundaries, and maximum flooding surfaces are employed for this purpose. Only those patterns that help to reveal transgressions and regressions on timescales of epochs and periods are considered, because our whole analysis is focused only on long-term shoreline shifts. Our second step is to compare the established regional transgressions and regressions with the global eustatic curve. For this purpose, the curve proposed recently by Haq and Schutter (2008), who improved the Phanerozoic curve proposed by Haq and Al-Qahtani (2005), is preferred. Only the long-term trends depicted by these authors are considered (Fig. 2). The highly-accurate eustatic reconstructions by Johnson et al. (1985) (reprinted in Ogg et al., 2008) and Johnson (2006, 2010) are not addressed for three reasons. Firstly, these authors aim to constrain short-term global sea-level changes. Secondly, these records are devoted to differing time intervals (Silurian in the case of Johnson (2006, 2010) and Devonian in the case of Johnson et al. (1985)), and it is questionable whether it would be possible to combine them. Thirdly, the curve by Johnson et al. (1985) is essentially regional. The third step of our analysis is a comparison of coincidences and differences between the regional shoreline shifts and eustatic fluctuations in light of tectonic activity and sediment supply. In the case of coincidence of transgressions with eustatic rises and regressions with eustatic falls, it is sensible to accept the dominance of eustatic control on the shoreline shifts. In the case of differences, subsidence or uplifts may be hypothesized as well as significant increases/decreases in the sediment supply to the basin (cf. Ruban, 2011a). The eustatic curve of Haq and Schutter (2008), which is preferred for this study, may also incorporate the influences of regional tectonic activity or sediment supply variations if these processes affect the stratigraphic records from which it is composed. Although any eustatic reconstruction cannot avoid this type of uncertainty, the long-term trends presented by Haq and Schutter (2008) are generally appropriate because they exhibit the same late Silurian–Middle

Devonian fall-rise global sea-level cycle that was depicted earlier by Hallam (1984), even if this study indicated an earlier lowstand peak. One may also question whether the Haq and Schutter (2008)'s reconstruction is itself influenced by interpretations made on the northern Gondwanan margin. Although it is likely that the Haq and Schutter's (2008) curve is based partly on data from Arabia, an important constituent of the Gondwanan margin (as this region was in the focus of the preceding model (Haq and Al-Qahtani, 2005)), significant constraints from North American and other regions of the world were also employed by Haq and Schutter (2008). Moreover, it was likely geological development of the Proto-Pacific, rather than the Gondwanan domain, was crucial for inducing eustatic changes (Ruban et al., 2010).

4. Results

4.1. Long-term shoreline shifts in the cratonic domains

Marine sedimentation occurred across a large territory in northwestern Africa during the late Silurian–Middle Devonian (Guiraud et al., 2005). Regional-scale hiatuses marked the start and the end of the Early Devonian, the size of sedimentation basin shrunk locally throughout the entire studied interval (e.g., the areas of southern Tunisia and Illizi-Ghadamis), and continental sedimentation (e.g., the Tadrart Formation) was relatively widespread in the Early Devonian (Guiraud et al., 2005; see also Spina and Vecoli, 2009) (Fig. 3a). Considering changes in shoreline position depicted by Guiraud et al. (2005), it becomes evident that the shoreline shifts were minor: the sea regressed from the Silurian to the Early Devonian, and then transgressed in the Middle-Late Devonian (Fig. 4). This evidence implies that the late Silurian–Middle Devonian time interval was embraced in northwestern Africa by a long-term regression–transgression cycle with a prominent seaward position of the shoreline during the Early Devonian (Fig. 3a).

Marine environments were more restricted in northeastern Africa during the late Silurian–Early Devonian (Guiraud et al., 2005). There, a significant hiatus encompassed the Silurian/Devonian boundary, deposition of continental siliciclastic sediment was especially widespread in the Early Devonian (e.g., the Tadrart Formation and the Ouan Kasa Formations in the Al Kufrah Basin), and conditions of terrestrial sedimentation and non-deposition characterized the territory of southwestern Sinai throughout the entire studied time interval (Guiraud et al., 2005; see also Le Heron and Howard, 2012) (Fig. 3b). Guiraud et al. (2005) depicted broad changes in the position of the shoreline: it shifted far northwards from the Silurian to the Early Devonian to be followed by strong (but not as strong as the previous regression) transgression in the Middle-Late Devonian (Fig. 4). These observations permit us to postulate a long-term regression–transgression cycle during the late Silurian–Middle Devonian in northeastern Africa; the shoreline retained its most seaward position in the Early Devonian (Fig. 3b).

Mid-Paleozoic marine strata, including the Jauf Formation, are reported from only a relatively small portion of Arabia, but it is hypothesized that the true extent of the sea was larger and that a significant volume of deposits was eroded in the Late Devonian (Sharland et al., 2001). The late Silurian–Middle Devonian deposition occurred in a cyclic manner (Sharland et al., 2001; see also Stump and Van der Eem, 1995; Wender et al., 1998; Al-Ghazi, 2007; Al-Harbi and Khan, 2008). Simmons et al. (2007) indicated three maximum flooding surfaces, namely the S20 (417.5 Ma), D10 (408.0 Ma), and D20 (400.0 Ma) surfaces. Considering the Devonian absolute time scale (Ogg et al., 2008), these surfaces are Pridoli, Pragian, and Emsian in age respectively. The same authors also delineated two major sequence boundaries beyond the limits of the studied geologic time interval, i.e., the S20 SB (422.0 Ma) and D30 SB (369.0 Ma) sequence boundaries, which are Ludlow and Famennian in age respectively (Simmons et al., 2007; see Ogg et al., 2008 for absolute ages of time units). As shown clearly by Sharland et al. (2001), the sea reached its maximum extent when the D20 maximum flooding surface was formed; in contrast, the area of deposition was restricted in the late Silurian and near the end of the Middle Devonian (Fig. 3c). These observations suggest that the transgression–regression long-term cycle took place in Arabia during late Silurian–Middle Devonian geologic time interval, and that the shoreline occupied its most landward position in the late Early Devonian (Fig. 3c).

4.2. Long-term shoreline shifts in the Tethys Himalaya

Both continental and marine sedimentation took place in the Tethys Himalaya during the late Silurian–Middle Devonian (Raju, 2007). The late Silurian is dominated by marine facies; erosion is reported from the Silurian–Devonian transition in South Zanskar and Spiti, but a gradual transition between the underlying Bamras Formation and the overlying Muth Formation took place in the Kumaun Basin; the Muth Formation bears both marine and terrestrial facies; deposition of the marine Lipak Formation started already in the Givetian; there was local advance of continental paleoenvironments in the Late Devonian (Aishmuqam Formation of the Kashmir Basin and the Jumboudiyar Formation of the Kumaun Basin), which however, did not interrupt the general trend towards an increase in marine sedimentation (Raju, 2007; see also Bhargawa and Bassi, 1986; Draganits et al., 2001, 2002; Singh et al., 2004; Parcha and Pandey, 2011; Sciunnach and Garzanti, 2012) (Fig. 3d). All of this information allows us to establish the regressive–transgressive cycle in the Tethys Himalaya during the late Silurian–Middle Devonian interval (Fig. 3d). The regression peaked in the Early Devonian, but the co-occurrence of marine and continental facies in the Muth Formation (Raju, 2007) does not imply that this seaward shoreline shift was remarkable.

4.3. Synthesis and further interpretations

The comparison of the recorded shoreline shifts in the four regions of the northern Gondwanan margin permits two interesting considerations. In northwestern and northeastern Africa and the Tethys Himalaya, a more or less similar regressive–transgressive pattern is registered (Fig. 3a, b and d). In these regions, the shorelines occupied their most seaward positions in the Early Devonian. Arabia, however, represents a striking exception. There, the sea transgressed to reach its maximum extent in the second half of the Early Devonian (Fig. 3c). This is evidence of heterogeneity of long-term shoreline shifts along the northern Gondwanan margin during the late Silurian–Middle Devonian. This is especially important considering the position of Arabia between northern Africa and the Tethys Himalaya (Fig. 1).

A comparison of the documented long-term regional shoreline shifts with the long-term global eustatic changes reconstructed by Haq and Schutter (2008) shows that the common regressive-transgressive pattern reported from both the cratonic domains of northern Africa and the Tethys Himalaya coincides well with global sea-level fall that peaked in the Early Devonian and was followed by rise later in the Devonian (Figs. 2 and 3). Along the northern margin of Gondwana, only shoreline shifts in Arabia differed from this basic pattern. Therefore, there was a strong eustatic control on the long-term late Silurian–Middle Devonian shoreline shifts on the northern Gondwanan margin, with Arabia representing the only noted exception. This conclusion also suggests that long-term shoreline shifts differed from the relatively short-term shifts that have been registered on the same northern Gondwanan margin (Ruban, 2011a).

5. Discussion

5.1. Possible imprints of regional tectonics on regional transgressions and regressions

Besides eustasy, tectonic activity can exert an important control on shoreline shifts (e.g., see review by Lovell, 2010). It is evident that the rate of subsidence may exceed the strength of eustatically-driven regression with landward shoreline shift as a result, and, vice versa, the rate of uplift may exceed the strength of eustatically-driven transgression with seaward shoreline shift as a result. Smaller vertical tectonic motions can amplify, or alternatively reduce, the strength of eustatically-driven transgressions and regressions. A suitable approach to detect the possible imprints of regional tectonic activity on the documented shoreline shifts is to check the coincidence of the latter with the global eustatic shifts (Ruban, 2011a). On the northern Gondwanan margin, the late Silurian–Middle Devonian long-term shoreline

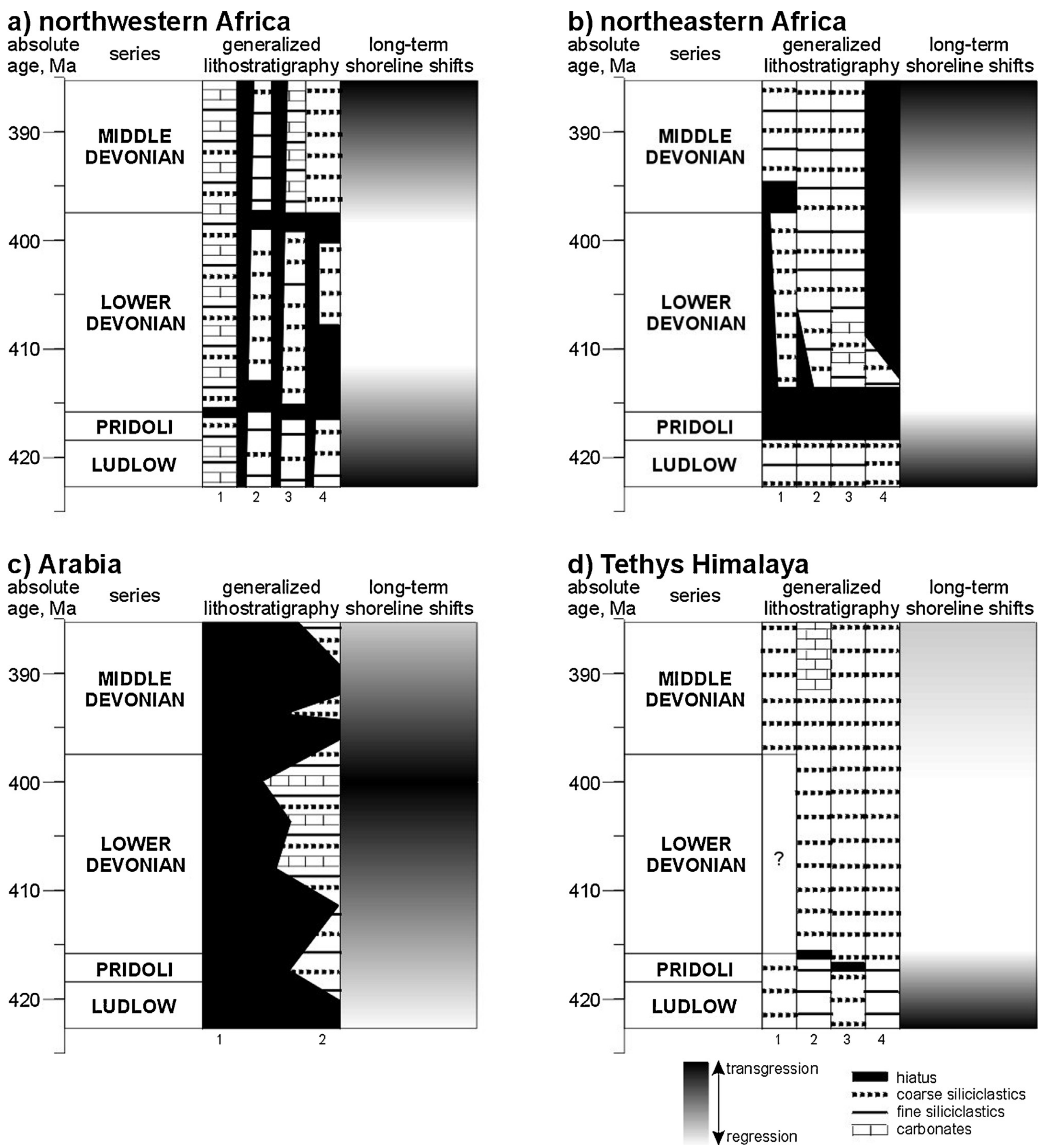

Fig. 3. Late Silurian–Middle Devonian shoreline shifts on the cratonic margin of northern Gondwana (chronostratigraphy after Ogg et al., 2008; see Fig. 1 for more details). See text and also Fig. 4 for interpretations of long-term shoreline shifts. The accuracy of correlations depends on the data quality in the original sources (see text and below). Data on earlier and later intervals are also considered in order to judge the strength of the registered transgressions and regressions. Numbers: (a) 1, Morocco; 2, southern Tunisia; 3, Illizi-Ghadamis, 4, Murzuq (lithostratigraphy adapted from Guiraud et al., 2005); (b) 1, Al Kufrah; 2, East Cyrenaica; 3, northwestern Egypt, 4, southwestern Sinai (lithostratigraphy adapted from Guiraud et al., 2005); (c) 1, southwest; 2, northeast (lithostratigraphy adapted from Sharland et al., 2001; Simmons et al., 2007); (d) 1, Kashmir; 2, South Zanskar; 3, Spiti; 4, Kumaun (lithostratigraphy adapted from Raju, 2007).

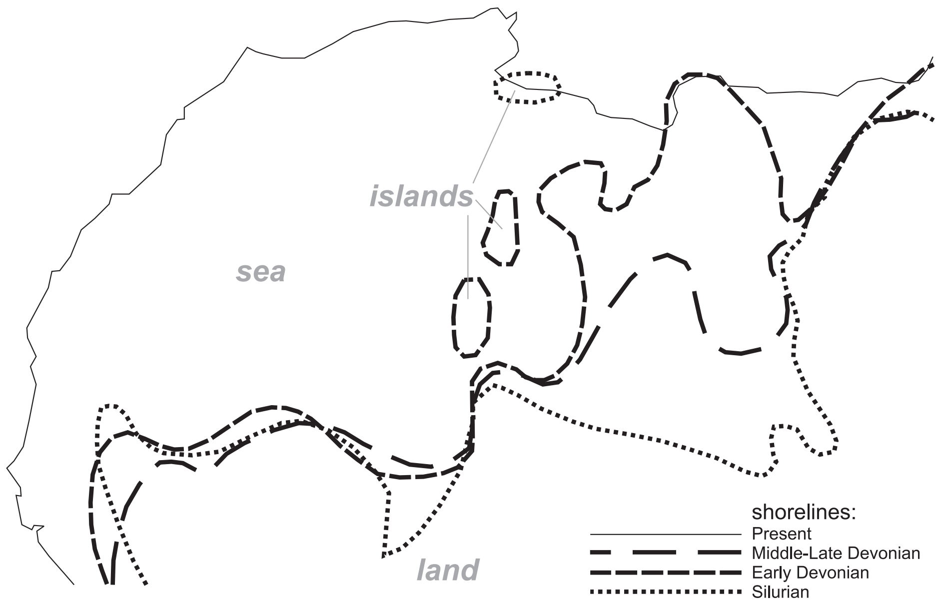

Fig. 4. Middle Paleozoic shoreline shifts in northern Africa (position of shorelines in the different geologic time slices is adapted from Guiraud et al., 2005). Note that Guiraud et al. (2005) did not depict palaeogeography for the part of the Atlasic domain in northwestern Africa in their reconstructions.

shifts in three major regions (northwestern and northeastern Africa and the Tethys Himalaya) coincided well with the long-term eustatic trends documented by Haq and Schutter (2008). Such a coincidence does not imply any significant tectonic control on the former (Fig. 5). One should note, however, that the horizontal distance of shoreline shifts was larger in northeastern Africa than it was in northwestern Africa (Fig. 4). Also, the magnitude of eustatic fall observed during the studied time interval (Fig. 2) was not exceptionally large; there were stronger falls in geological history (Haq and Al-Qahtani, 2005; Haq and Schutter, 2008). Therefore, the more pronounced Early Devonian regression in northeastern Africa may have been amplified by regional uplift that re-inforced the eustatically-driven seaward shift of the shoreline. As for Arabia,

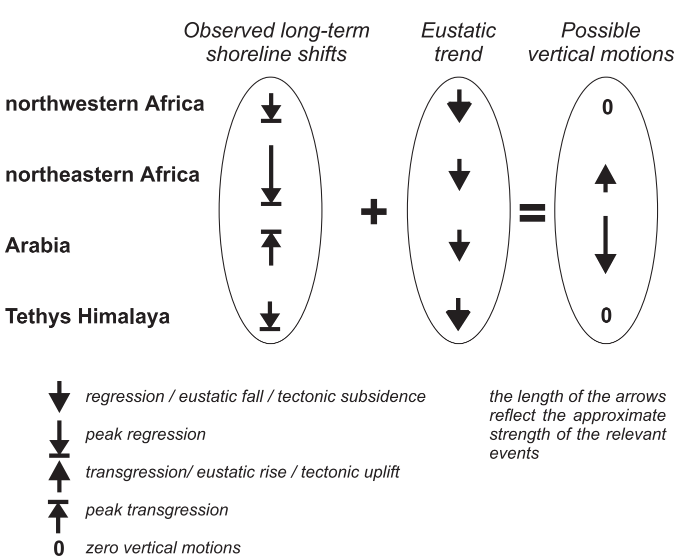

Fig. 5. Eustatic-tectonic interplay on the northern Gondwanan margin in the Early Devonian (i.e., in the midst of the studied geologic time interval). Possible vertical tectonic motions are derived from the analysis of the observed long-term shoreline shifts and the eustatic trends (see text for more explanations). The factors of sediment supply and margin geometry are not considered; see text for relevant discussions.

only regional subsidence at rates faster than those of eustatic sea level change can explain the long-term transgression that peaked in the Early Devonian (Fig. 5).

The mid-Paleozoic tectonic deformations on the northern Gondwanan margin were relatively short term and have been recognized at the level of stages (Sharland et al., 2001; Guiraud et al., 2005). However, these compressional tectonic settings would have tended to facilitate the Early Devonian regression (cf. Guiraud et al., 2005), and it is possible that the above-mentioned stronger shoreline shifts in northeastern Africa may have been the result of such deformations. Pre-rifting uplift can be expected directly before the opening of the Paleo-Tethys Ocean in the Middle-Late Devonian (von Raumer and Stampfli, 2008). However, the sea transgressed over northern Africa and the Tethys Himalaya together with eustatic rise (Haq and Schutter, 2008) at the end of the studied time interval (Figs. 2 and 3). Further investigations are necessary in order to understand whether this pre-rifting uplift was limited enough to be overcome by the extent of the eustatically-driven transgression in the Middle Devonian, or whether it occurred in the Early Devonian and facilitated the regressions documented in that epoch (Fig. 3). Similarly, one may hypothesize that the uplift was especially strong at a junction of the branches of the future Paleo-Tethys (von Raumer and Stampfli, 2008) (Fig. 1); in such a case, it might have been especially important for Arabia, which would explain the Middle Devonian regressive setting of this region (Fig. 3c). However, post-rifting extension of the continental crust has also been linked to subsidence (McKenzie, 1978; Sawyer, 1985; Kirschner et al., 2010). If so, further studies are necessary to establish the exact timing of rifting on the northern Gondwanan margin. Indeed, differences in the timing of rifting stages along the northern Gondawan margin may be responsible for some of the differences in transgression/regression history along this margin.

On longer time scales (epochs and periods), one of the most efficient tectonic mechanisms responsible for vertical tectonic motions is dynamic topography (Lithgow-Bertelloni and Gurnis, 1997; Lithgow-Bertelloni and Silver, 1998; Conrad and Gurnis, 2003; Conrad et al., 2004; Husson, 2006; Heine et al., 2008; Moucha et al., 2008; Spasojevic et al., 2008; Conrad and Husson, 2009; DiCaprio et al., 2009; Anderson and Anderson, 2010; Lovell, 2010; Jones et al., 2012; Shephard et al., 2012; Spasojevic and Gurnis, 2012). Generally, convergent plate boundaries, such as the one bordering northern Gondwana in the late Silurian–Early Devonian, are associated with long-wavelength and negative dynamic topography. This is because plate convergence places dense slabs of cold lithosphere into the upper mantle, which can induce active mantle downwelling that depresses the Earth's surface above them by up to ~1 km (e.g., Hager et al., 1985; Billen et al., 2003; Husson, 2006). The location of surface subsidence depends on the location of the mantle slab relative to the plate boundary, and can change with time. For example, the current drainage patterns of the Amazon River resulted from eastward tilt of South America that developed during the Miocene; this tilt is thought to be the direct result of westward motion of South America over the subducted Nazca slab (Shephard et al., 2010). Similarly, several hundred metres of anomalous Cenozoic depression of central and eastern North America is thought to have resulted from westward motion of that continent over the subducted Farallon slab in the lower mantle (Spasojevic et al., 2009). This excess depression of the continental margin may have significantly reduced sea level change along the US east coast compared to global estimates (Müller et al., 2008; Spasojevic et al., 2008). These recent examples may serve as useful analogues for the excess subsidence observed in Arabia: obduction on the northern boundary of Gondwana (von Raumer and Stampfli, 2008) places slabs of lithosphere into the mantle. Depending on the time-dependent dynamics of obduction and slab descent (which may be geographically complex – e.g., Liu and Stegman (2011)), the location of downwelling and associated surface depression may change relative to the location of the continental margin. This may variously have permitted subsidence of the Rheic ocean seafloor in some locations and subsidence of the Gondwana continental interior in others, as is apparent in Arabia.

The influence of the hypothesized subsidence is not readily discernable in most of the documented records (Fig. 3a, b, d). In three of four considered regions, transgressions and regressions followed the global eustatic trend over long time scales. One possible explanation is that this subsidence occurred close to, or seaward of, the continental margin, in which case tectonic deformations (Sharland et al., 2001; Guiraud et al., 2005; Ruban et al., 2007a) may have recompensed for its effect. It should also be noted that the weak shoreline shifts established in northwestern Africa (Fig. 4a) could be explained by the influence of obduction-related subsidence that may have diminished the eustatically-driven seaward shoreline shift. However, this hypothesis requires further verification. Only in Arabia is the reversed trajectory of shoreline shifts observed (Fig. 3c). Is it possible that the significant subsidence in this region was linked to dynamic topography associated with descent of slabs placed in the mantle by obduction along the edge of the supercontinent? Although the available data do not permit us to answer this question with certainty, it is evident that Arabia was located quite far from the obduction zone (Fig. 1; see also von Raumer and Stampfli, 2008), which would require significant landward transport of mantle slabs that could be accomplished by northern motion of Gondwana as it overrides the Rheic Ocean (e.g., Collins, 2003) and/or flat-slab subduction of the Rheic ocean slab. Such a flat-slab subduction occurred in North America, and is thought to have produced significant orogeny inland of the continental margin (which made the Rocky Mountains), followed by an episode of intraplate volcanism after the slab began to descend (Humphreys, 1995; Farmer et al., 2008). Although more geological data from Arabia should be further involved, it is interesting to note that this domain apparently remained active in the late Paleozoic, Mesozoic, and early Cenozoic (Le Nindre et al., 2003), and, if so, it may have been similarly active in the earlier times. There is also evidence of diastrophism during the early Silurian-late Early Devonian (Stump and Van der Eem, 1995). At a minimum, these observations do not contrast with the considerations presented above. Most probably, the key to understanding the Early Devonian subsidence in Arabia lies in the detection of the force(s) responsible for and linked to the further opening of the Paleo-Tethys Ocean and its propagation via three branches (as depicted by von Raumer and Stampfli (2008)). Mechanisms such as those described by Leng and Zhong (2010) cannot be totally excluded.

The northern Gondwanan margin may serve as an interesting example of a domain, influenced by both plate tectonic forces (sensu stricto) and mantle-related vertical motions, which interact on different spatial and temporal scales. It is difficult to determine which may offer a more important control on shoreline shifts. However, taking into account the general geodynamic setting of this margin (e.g., Guiraud et al., 2005; von Raumer and Stampfli, 2008), one can hypothesize that dynamic topography may have exerted a greater control because the above-mentioned transgressions and regressions embraced large parts of the continental interiors located far from the plate edges. On the other hand, tectonic processes (e.g., the mentioned obduction), and their interaction with mantle flow, can induce vertical motions of continents across large areas (e.g., Humphreys et al., 2003).

The possible tectonic imprints on the documented shoreline shifts cannot be discussed without consideration of sediment supply variations. Voluminous deposition of sediments can minimize both eustatic and tectonic controls. For example, siliciclastic sediments derived from the central parts of Gondwana and deposited in northern Africa during the Early-Middle Devonian (Guiraud et al., 2005; Spina and Vecoli, 2009; Le Heron and Howard, 2012) might have contributed to seaward shoreline shift even if the thickness of these deposits was not large. Moreover, it is possible that accumulation of this detritus in the Early Devonian might have partly recompensed for tectonic subsidence (if this actually occurred). In northern Africa, the true thickness of the relevant deposits may have been relatively significant but could have been diminished later by the Middle/Late Devonian erosion event (Guiraud et al., 2005). In the Tethys Himalaya, the thickness of the relevant deposits is large (Raju, 2007), making global eustasy the main inferred control on shoreline shifts. Continental margin topography may also have been a factor. For instance, if the surface in northwestern Africa was generally steeper than in northeastern Africa, this fact may provide an appropriate explanation for stronger transgressions and regressions in the latter region.

5.2. Comparison with selected peripheral terranes

According to the plate tectonic reconstruction of von Raumer and Stampfli (2008), a large chain of terranes constituted the edge of the northern Gondwanan margin in the late Silurian–Middle Devonian to form the Greater Galatian Superterrane after complete separation from Gondwana in the Middle-Late Devonian (Fig. 1). It is worth considering the long-term shoreline shifts that occurred there within the studied time interval. For this purpose, data from selected terranes are considered. Cantabria was located in the southeastern part of the future Greater Galatian Superterrane and close to northeastern Africa (von Raumer and Stampfli, 2008). The spatial distribution of hiatuses in particular areas (Vera, 2004) suggests that its shoreline was rather stable during the late Silurian and the early Early Devonian, but was followed by regression that culminated in the Late Devonian. The Carnic Alps were situated in the same portion of the superterrane, but far eastwards and near Arabia (von Raumer and Stampfli, 2008). The stratigraphic architecture and the distribution of hiatuses (Schönlaub and Histon, 1999; Venturini, 2002; Brett et al., 2009) show that, after the precededing long-term transgression (interrupted by the shorter shoreline shifts), the sea retained it maximal extent in this region during the Early Devonian, and the regressive trend became established since the Middle Devonian. The Greater Caucasus lay somewhere near the Carnic Alps (Ruban et al., 2007b). The mid-Paleozoic palaeoenvironmental changes in this region were reconstructed by Gutak and Ruban (2007) and Ruban (2008). These interpretations as well as the original lithostratigraphical data (Robinson, 1965; Kizeval'ter and Robinson, 1973; Obut et al., 1988) provide evidence of the long-term lowstand that encompassed the entire late Silurian–Middle Devonian interval and the regression peak near the Silurian-Devonian transition in the Greater Caucasus. Additional evidence derives from the Taurides (Göncüoğlu et al., 2004; Moix et al., 2008), which belonged to the Cimmerian terranes that derived from Gondwana in the late Paleozoic together with the opening of the Neo-Tethys Ocean; the Taurides were therefore a part of the northern Gondwanan margin in the mid-Paleozoic (Şengör, 1979; Stampfli and Borel, 2002; Göncüoğlu et al., 2004; Ruban et al., 2007a; Moix et al., 2008). Although the long-term late Silurian–Middle Devonian shoreline shifts cannot be traced there with precision, unconformities are established at the Silurian-Devonian transition and near the Lower-Middle Devonian transition or just above the latter (Göncüoğlu et al., 2004; Moix et al., 2008). A long-term regression peak may have occurred in the Early Devonian, and, if so, it was comparable to peaks registered on the northern Gondwana margin (Fig. 3a, b and d).

The examples given above suggest certain differences in the late Silurian–Middle Devonian shoreline shifts in the peripheral terranes of Gondwana. These local transgressions and regressions differed also from those in the neighbouring cratonic domains of the northern Gondwanan margin (Fig. 3) and from those occurring globally (Haq and Schutter, 2008). This conclusion, however, is not surprising, because the peripheral terranes (first of all the future Galatian terranes) were strongly affected by obduction on the southern periphery of the Rheic Ocean, resulting from continent-arc collision (von Raumer and Stampfli, 2008). In other words, the chain of terranes was tectonically active, and the related deformations should have left a strong imprint on regional transgressions and regressions there, changing the trends linked to the eustatic fluctuations. Interestingly, the same assumption was not verified at a shorter time scale (Ruban, 2011a).

6. Conclusions

The late Silurian–Middle Devonian long-term shoreline shifts (regression followed by transgression with a pronounced regression peak in the Early Devonian) were generally the same in northern (northwestern and northeastern) Africa and the Tethys Himalaya, which were the constituents of the northern Gondwanan margin. These shifts coincided well with the long-term global eustatic changes (Haq and Schutter, 2008), which permits us to emphasize the importance of eustatic control. In contrast, a transgression–regression cycle (i.e., of the opposite sense) is registered in Arabia, and this difference can be explained by significant subsidence of that domain. Indeed, the potential importance of regional tectonic activity, sediment supply from the eroded source areas, and changes in dynamic support of continental surface topography, which may have exerted additional controls on regional shoreline shifts, cannot be excluded. Changes to the available eustatic curve (Haq and Schutter, 2008), which may result from the incorporation of additional stratigraphic constraints, may cause some of the conclusions presented above to be re-evaluated in the future.

Conclusions from the present study, which examines shoreline shifts occurring on timescales of epochs and periods, differ from those made on the basis of a shorter time scales (Ruban, 2011a), which highlights the importance of separate examination of shoreline shifts of different orders. The accuracy of available eustatic reconstructions (e.g., Haq and Schutter, 2008) also remains a subject for further debate. Data from a single domain, even if that domain is as large as the northern Gondwanan margin, cannot constrain global sea-level rises and falls because vertical motion of the continental margin in a specific location or region may influence the sea level record there. Instead, a broad inter-regional (global in an ideal case) correlation of such data may be the only possible instrument for verification and improvement of the available eustatic reconstructions (e.g., Embry, 1997; Hallam, 2001; Kominz et al., 2008; Miall, 2010; Ruban et al., 2012). Finally, the present analysis highlights the importance of regional lithostratigraphical syntheses coupled with facies interpretations, which feed us with the data necessary for construction of general palaeoenvironmental and geodynamic models.

Acknowledgements

The authors gratefully thank J. Rose (UK) for his editorial support, P.G. Eriksson (South Africa) and another anonymous reviewer for their constructive suggestions, as well as M.I. Al-Husseini (Bahrain), M.C. Göncüoğlu (Turkey), R. Guiraud (France), N.M.M. Janssen (Netherlands), M.E. Johnson (USA), B. Lovell (UK), M. Pondrelli (Italy), B. Ran (China), W. Riegraf (Germany), C. Wilhem (Switzerland), S.O. Zorina (Russia), and many other colleagues for discussions and/or help with literature. This work was partially supported by NSF grant EAR-1151241 (C.P.C.).

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